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FLAMMABILITY TESTING CONDUCTED IN SUPPORT OF APOLLO 13

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ABSTRACT

In support of the Apollo 13 investigation of the oxygen tank failure, flame propagation rates were determined for Teflon insulation in cryogenic and ambient temperature oxygen for upward, downward, and zero "g" burns. The propagation rates depended heavily on configuration and varied from 4.8 to 10.9 cm/sec for upward one "g" burns to 0.48 cm/sec for zero "g" burns.

In addition to the flame propagation rates, tests were conducted to determine if Teflon burning in cryogenic oxygen could ignite metals (promoted ignition) with which it came in contact. Tests conducted on various metal alloys used in the oxygen tank indicated that most of the alloys could be ignited by burning Teflon in certain configurations.

After the propagation rates and promoted metal ignitions had been evaluated, a test was conducted on a quantity gauge and wire harness used in the oxygen tank to determine if flame propagation to the tank wall was possible. Propagation of the wire bundle after ignition resulted in a catastrophic failure of the test vessel in the area of the quantity gauge.

INTRODUCTION

Failures of ground oxygen storage and handling systems have been noted frequently in the past. During the trans-lunar phase of the Apollo 13 mission a similar failure occurred in one of the service module compartments; the item that failed was a cryogenic oxygen storage tank which provides oxygen to the crew and fuel cells. The tank consisted of a double-wall, vacuum-jacketed vessel containing a heater, quantity gauge, and two circulating fans, all of which were electrically operated. The tank also contained conductors using polytetrafluoroethylene (Teflon) as insulation and electrical feedthroughs which were all in direct contact with high pressure oxygen. This condition presented a potential problem in that a fire could originate in the electrical system, propagate along the wire insulation, and eventually cause a catastrophic failure of the system.

A major investigation was conducted to explain the tank failure mechanism. It became obvious in the early stages of this investigation that the failure was indeed the result of rapid oxidation inside the tank and that an explanation of the failure would require a study of the flammability properties of tank materials. The probability of ignition of these materials inside the tank and their propagation rates were the object of the study reported herein.

Upward and downward flame propagation rates of the tank electrical insulation were evaluated in both cryogenic and ambient temperature oxygen in one "g" condition at MSC. Zero "g" propagation rates were determined in a zero "g" facility located at Lewis Research Center.

As part of the ignition studies, the promoted ignition (ref. 1) of metals by burning Teflon was investigated. Tests of this type were conducted in both one "g" and zero "g" conditions on a selected number of metal alloys. Spark ignition of the same materials are discussed in another paper of this symposium (ref. 2).

The results of the flame propagation studies and ignition studies were tehn used in testing a flame propagation model for the failed oxygen tank. To evaluate the flame propagation model, a partial configuration of the oxygen tank quantity gauge and fan motor and heater wire bundles was conducted. Results of the partial configuration test, along with the results of the flame propagation and promoted ignition studies, are presented in this paper.

ENVIRONMENTAL TEST CONDITIONS AND IGNITION TECHNIQUE

The tests discussed in this paper were conducted in an oxygen environment at a pressure of 645 ±20 newtons/cm^2 (940 ±30 psia) and at a temperature of -118° ±15°C; these conditions were approximately those in the Apollo 13 oxygen tank at the time of failure. In addition, propagation rates were determined at ambient temperature and at a pressure of 645 ±20 newtons/cm^2, the conditions of the portion of the electrical conduit external to the oxygen tank.

In each test the sample was ignited by wrapping the material with a few turns of 26 gauge nichrome wire, initially applying 5 amps at 28 volts dc for 3 to 5 seconds to provide a localized warmup, and then raising the ignitor power to 10 amps at 28 volts dc until ignition took place (usually a few seconds later).

PROPAGATION RATE TESTS

A study was conducted to measure the upward and downward propagation rates of Teflon insulation (0.03 cm thick) on electrical wires similar to those in the Apollo service module oxygen tank. Inasmuch as the tank was in a zero "g" gravity field at the time of failure, an investigation of propagation rates in this environment was also conducted. Since most of the wires were of different colors, an objective of the study was to determine if the various color pigments used in the Teflon affected propagation rates.

Test Apparatus

One "g" - The chamber (fig. 1) used for the one "g" studies was equipped with a burst disc (2425 newtons/cm^2 burst pressure) oxygen purge, fill and vent lines, thermocouples, ignitor power feedthroughs, and a pressure transducer. The propagation rates of the Teflon insulation were determined by measuring the time necessary for the flame to propagate between two thermocouples 3.7 cm apart. The use of three thermocouples in the propagation path provided additional rate determinations. Details of the test sample, ignitor position, and thermocouple locations are shown in figure 2.

Zero "g" - The zero "g" tests were conducted in the zero "g" facility at Lewis Research Center. Five seconds of zero "g" time were attained during each test. Propagation rates were determined from movies taken during each test by correlating frame speed with travel of the flame along the wire bundle. Figure 3 shows the test specimen and ignitor configuration for the zero "g" tests.

Results

One "g" - The one "g" flame propagation rates for single wires and wire bundles at cryogenic and ambient temperatures are presented in tables I and II. As mentioned previously, insulation with different colors were chosen for the tests; however, there were no significant differences in the propagation rates. The results represent average determinations for different color insulations. Where appropriate, standard deviations of the propagation rates are presented.

Zero "g" - The zero "g" flame propagation rates in cryogenic oxygen for wire bundles are presented in table III. Because of the complexity and cost of the testing, only a limited number of data points were obtained. The data as presented are the rates determined for each zero "g" test.

PROMOTED IGNITION

The objective of this study was to determine if burning Teflon could ignite metal alloys in the configuration (thickness, geometric relationship to fuel, edge condition, etc.) used in the oxygen tank.

Test Apparatus

Various materials and configurations tested in one "g" are shown in figure 4. Only one zero "g" test was conducted; this occurred on configuration 3 of figure 4. The test environment and ignition technique were the same as for the propagation rate studies except that in the promoted ignition tests a small cube of Teflon (1 or 2 gms) was ignited as the fuel to promote ignition of the metals. Test results were evaluated by monitoring temperature and pressure rise during the test and through post test inspection of the metal samples.

Results

Edge contact of 2024 aluminum with the fuel, as shown in configuration 1 of figure 4, did not result in ignition, whereas contact of the Teflon with the flat side of the aluminum (configuration 2) resulted in ignition in three tests. Moving the aluminum away from the Teflon a distance of 1.27 cm, and then of 0.64 cm (configuration 3), resulted in no ignitions for the limited number of tests conducted. Placing silicon steel specimens in contact with the Teflon fuel (configuration 4) resulted in ignition in all three tests conducted. In five tests of 5052 aluminum (configuration 5) conducted in one "g" and in a single zero "g" test, ignition did not occur. In configuration 6 the test specimen consisted of a 2.54 cm length of Inconel X750 electrical conduit containing 18 Teflon insulated wires. In each of three tests the Inconel tube and most of the wiring and insulation were consumed.

PARTIAL CONFIGURATION TEST

The objective of this test was to determine if flames would propagate in a configuration similar to that of the Apollo 13 tank and to determine if the flames would ignite metal components of this configuration.

Test Apparatus

The chamber used for this test was a stainless steel tee equipped with flanges. A camera viewport, electrical and hard line feedthrough, and conduit to the quantity probe interface were installed through the flanges. The chamber, which is shown schematically in figure 5, has a volume of approximately 10 liters. A pressure relief valve was provided which was designed to open at 722 newtons/cm^2. In addition, the test chamber contained a rupture disc to prevent failure of the test chamber in case of pressure relief valve malfunction.

Temperatures were monitored with 5 internal thermocouples, and pressure was measured by use of a pressure transducer. Color motion pictures were taken through the one available viewport at a speed of 24 frames per second. A second camera provided external color motion pictures of the conduit chamber interface, also at 24 frames per second. Three thermocouples were located in the region of the quantity gauge, as shown in figure 5. Two thermocouples measured internal chamber wall temperatures. Three thermocouples were installed on the external surface of the conduit as shown in figure 5 to measure propagation through the conduit.

The two fan motor wire bundles were routed downward to the quantity gauge and penetrated through openings in the quantity gauge to the conduit. All of the wiring (power and instrumentation wires representative of the Apollo tank) was routed through the conduit to a connector which provided the high pressure to ambient pressure interface. The insulation was ignited using the same technique as for the propagation rate studies.

Results

The propagation observed in the motion pictures of the inside of the chamber proceeded vertically downward on the fan motor wire bundle from the ignition site and ignited other wires intersecting its path and eventually reached the upper portion of the quantity gauge. The fire then propagated through the quantity gauge downward to the conduit chamber interface and ignited the metals in this region and burned a large hole in the chamber. The inside diameter of the penetration to the chamber was initially 1.27 cm but was opened up by the oxygen melting, burning, and cutting effect to a final diameter of 4.75 cm. This event occurred in approximately 0.5 second and permitted rapid venting of the high pressure oxygen. Time from ignition through the catastrophic tank burn through was approximately 31 seconds.

Figure 6 shows the pressure history during the test. The initial pressure rise occurred 24 seconds after ignition, and burn through occurred 6.5 seconds later, at which time the pressure decayed to one atmosphere in approximately 0.5 second. Temperature histories of both internal and external portions of the test apparatus are shown in figures 7 and 8.

DISCUSSION OF RESULTS

Propagation Rates

The method employed to determine flame propagation rates in this study is simple to use experimentally but has severe limitations when applied to certain sample configurations. Spurious flames, produced by the burning sample, can in some cases encounter the measuring thermocouple before the main flame front and result in erroneously large rates. These spurious flames are more frequently encountered in upward rate configurations than for other configurations (downward, horizontal) and could be the cause of the large deviations measured for the upward rates in this study. Standard deviations for the downward rates are in the range of 10 to 20% which is within the expected error range for normal variations in the burning process.

During the investigation, it was postulated that color pigments used in the insulation could affect the propagation rates through an interaction between the various pigments (metal oxides) and the polymer at high temperature. However, no differences in the propagation rates for several types of pigmented insulation were noted. The interaction of the polymer with the pigment apparently is not as important as the direct interaction of the polymer with the oxygen to produce COF_2, CF_4, and CO_2, as reported by Duus (ref. 3) for tetrafluoroethylene. Previous unpublished work performed at the MSC indicated that these components are the major products of combustion of Teflon.

The effect of test environment temperature on flame propagation is noticeable in the downward rate determinations. Downward propagation rates at -118°C are only one-half of those at 30°C. Results of 26 and 20 gauge wire upward propagation rates also show a larger rate at 30°C; however, the rates are only approximately one-third larger than those at cryogenic conditions.

Two previous studies, Kimzey (ref. 4) and Andracchio and Aydelott (ref. 5) have reported flame propagation studies of polymeric materials in zero "g". Kimzey found that Teflon was self-extinguishing in a zero "g". 3.4 newtons/cm^2 (5 psia) ambient temperature oxygen environment. These results are in contrast to the propagation rate determination of the present study of 0.48 ±0.25 cm/sec at 632 newtons/cm^2. The difference in these results undoubtly resulted from the different oxygen pressures used. Propagation rates for neoprene, polyurethene, Dacron, and silicone fuels were reported by Kimzey to be approximately 0.2 cm/sec at 3.4 newtons/cm^2 and 0.38 cm/sec at 10.3 newtons/cm^2 (15 psia). Andracchio and Aydelott, reported zero "g" flame propagation rates for thin plates of cellulose acetate of 2.2 to 4.4 cm/sec at 3.4 newtons/cm^2, depending upon the sample thickness used.

Despite the limitations of the propagation rate determinations, there is no apparent reason to believe that the zero "g" rates of Teflon are not representative of rates which could be encountered in oxygen systems of orbiting spacecraft. Any change in the zero "g" environment which could be produced by propulsion maneuvers would produce convection currents and therefore affect the propagation rates. The Teflon propagation rate data apparently constitute a lower bound to the propagation rate of this material in spacecraft oxygen systems.

Promoted Ignition

As mentioned previously, promoted ignition studies were conducted in a manner very similar to the study of Nihart and Smith (ref. 1). The promoting fuel used in their study was neoprene, whereas, in this study Teflon was used exclusively. As in this study, Nihart and Smith were also able to ignite Inconel X750, steels, and aluminum alloys. Effects of sample configuration, as investigated in the present study (and as might be expected), show that thin sections of the alloys are more easily ignited than larger samples.

Partial Configuration Test

Results from the partial configuration test of the quantity gauge and associated wire bundles show that the flame propagation and promoted ignition results are applicable to the configured oxygen tank system. The configuration test film determined the rate of propagation to be approximately 0.67 cm/sec, which is in good agreement with the propagation rate test result of 0.97 cm/sec for this condition. Ignitions of Inconel X750 and stainless steel occurred in the test; again, this effect could be predicted from the promoted ignition results.

CONCLUDING REMARKS

Flame propagation rates for Teflon electrical wire insulation typical of that used in the Apollo 13 cryogenic oxygen tank showed that upward propagation rates are larger than downward rates by approximately a factor of ten. Propagation rates in zero "g" at cryogenic temperature for wire bundles are approximately half of the corresponding one "g" downward rates. A change of temperature from approximately -118°C to 30°C increased the rates by approximately 100% for downward burns and by approximately 30% for upward burns. No effect of insulation color pigment on the flame propagation rates could be detected. The zero "g" Teflon propagation rates apparently constitute a lower bound flame propagation rate for this material applicable to orbiting spacecraft oxygen systems.

Promoted ignition of four metal alloys by burning Teflon showed that ignition and extensive burning occurred for thin sections of silicon steel. Ignition of Inconel X750 and two aluminum alloys occurred for certain configurations, and, once ignited, the test items burned to completion in almost all cases. No ignition of an aluminum alloy occurred in the only zero "g" promoted ignition test conducted. The limited zero "g" data do not permit any conclusions to be drawn for promoted ignition in that environment.

On a partial configuration of the oxygen tank quantity gauge and associated wire bundles, flames propagated along two wire bundles through the upper portion of the quantity gauge and ignited a portion of the conduit-chamber interface. This ignition resulted in a venting of high pressure oxygen over a period of 0.5 sec, during which severe burning of the conduit-chamber interface occurred.

ACKNOWLEDGMENT

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TABLE I. DOWNWARD PROPAGATION RATES

Wire gauge	Pressure, Newtons/cm^2	Temperature, °C	Rate, cm/sec	Number of tests
26 (bundle of four)	670	-118	0.97±0.15	4
26 (individual wires)	666	-118	0.58±0.05	8
22 (individual wires)	690	-118	0.58±0.05	8
22 (coaxial)	650	-118	0.81±0.25	5
20 (individual wires)	653	-118	0.79±0.10	8
26 (individual wires)	678	30	1.55±0.58	6
22 (individual wires)	654	30	1.07±0.13	9
20 (coaxial)	654	30	1.27±0.41	20
20 (individual wires)	662	30	1.37±0.23	4

TABLE II. UPWARD PROPAGATION RATES

Wire gauge	Pressure, Newtons/cm^2	Temperature, °C	Rate, cm/sec	Number of tests
26 (individual wires)	647	-118	5.75	2
22 (individual wires)	659	-118	10.4±5.34	8
20 (coaxial)	650	-118	7.9±2.14	4
20 (individual wires)	650	-118	4.8±2.29	11
26 (individual wires)	664	30	8.9±2.54	4
20 (coaxial)	660	30	10.9±3.81	
22 (individual wires)	662	30	8.6±3.56	10

TABLE III. ZERO "g" PROPAGATION RATES

Test item	Pressure, Newtons/cm^2	Temperature, °C	Rate, cm/sec	Number of tests
Wire bundles: 4 wires clear and white shrink tubing	632	-118	0.48±0.25	6

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APPARATUS FOR PROPAGATION RATE AND PROMOTED IGNITION STUDIES

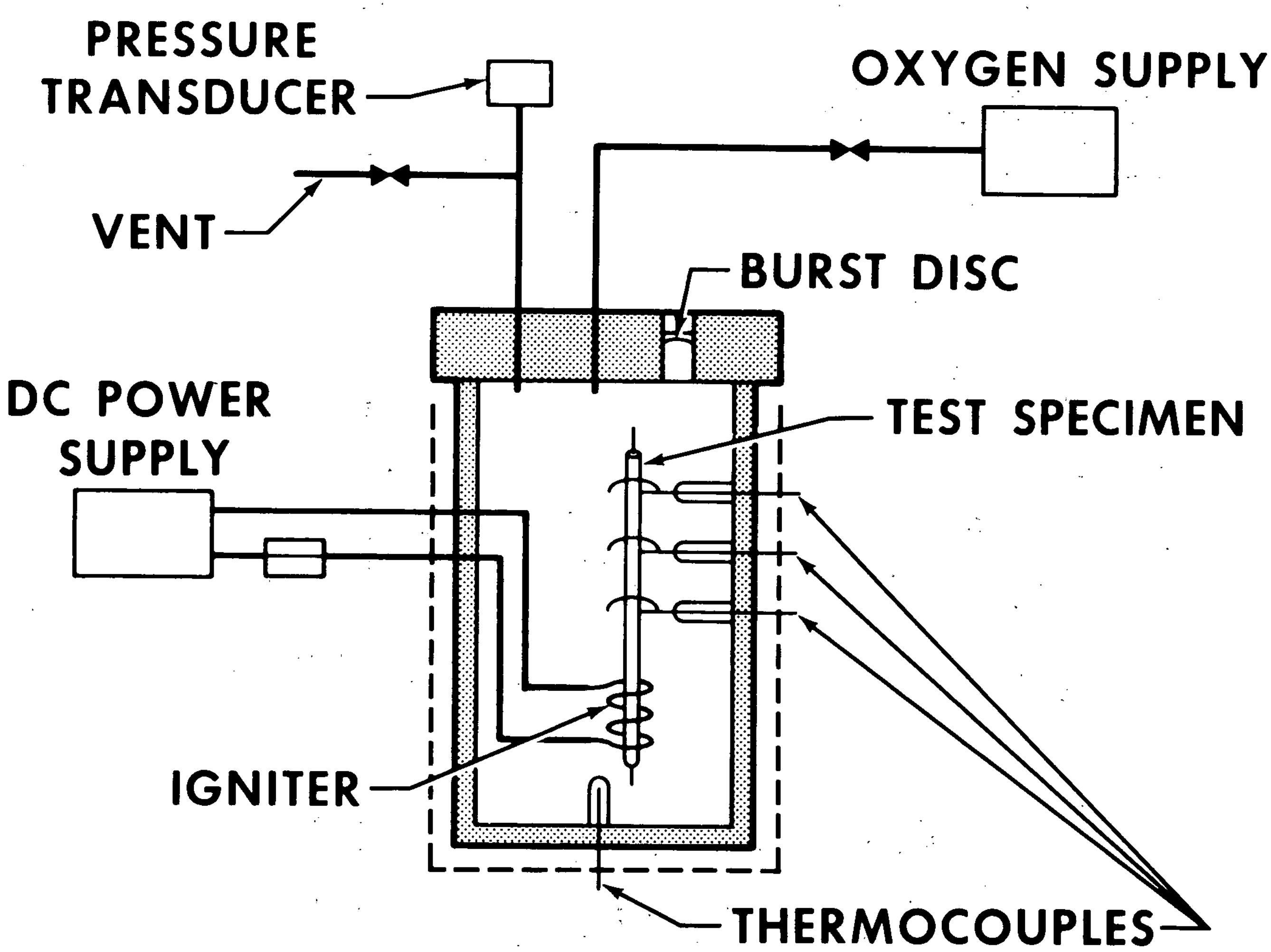

Figure 1.

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PROPAGATION RATE TEST CONFIGURATION

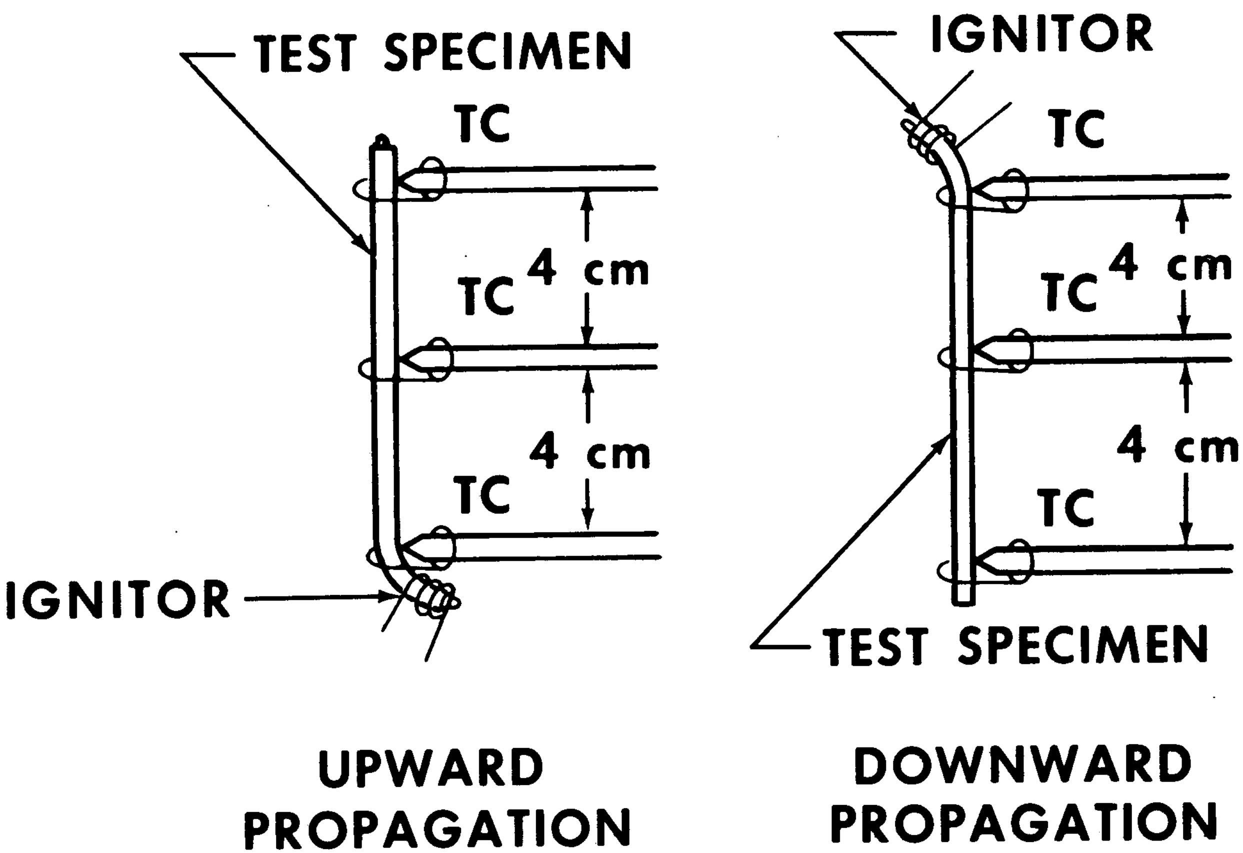

Figure 2.

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ZERO 'g' FLAME PROPAGATION CONFIGURATION

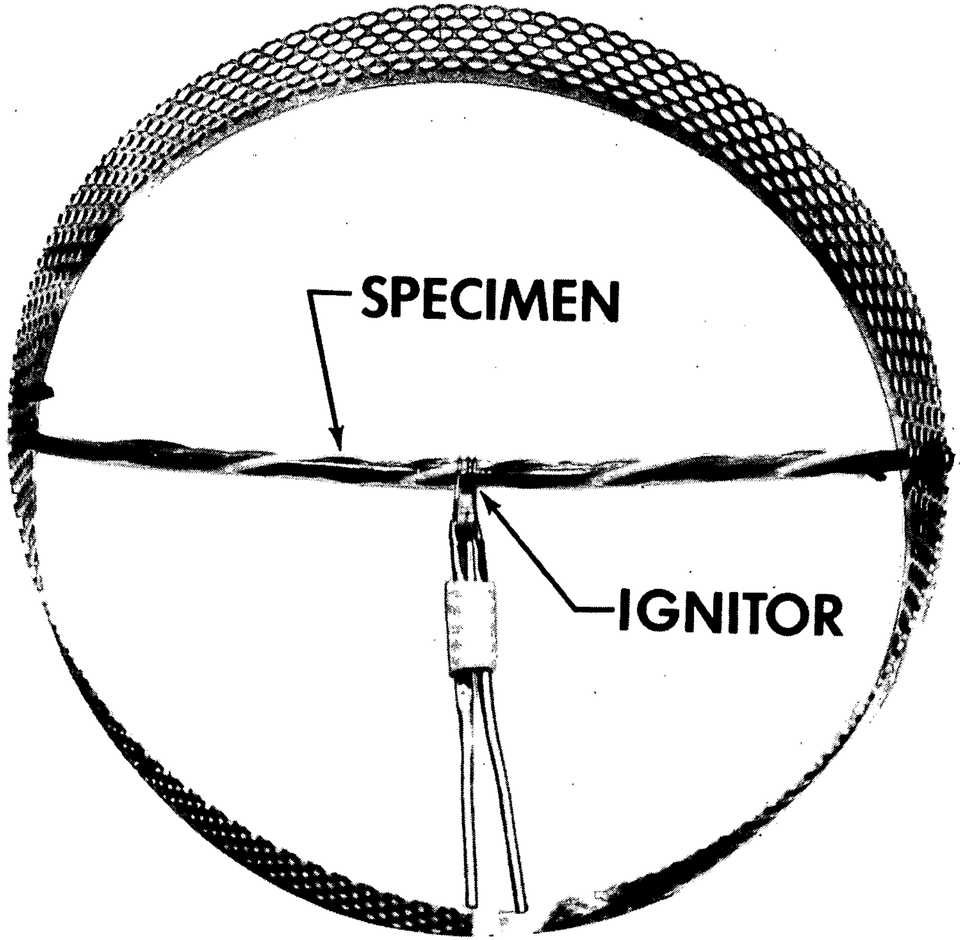

Figure 3.

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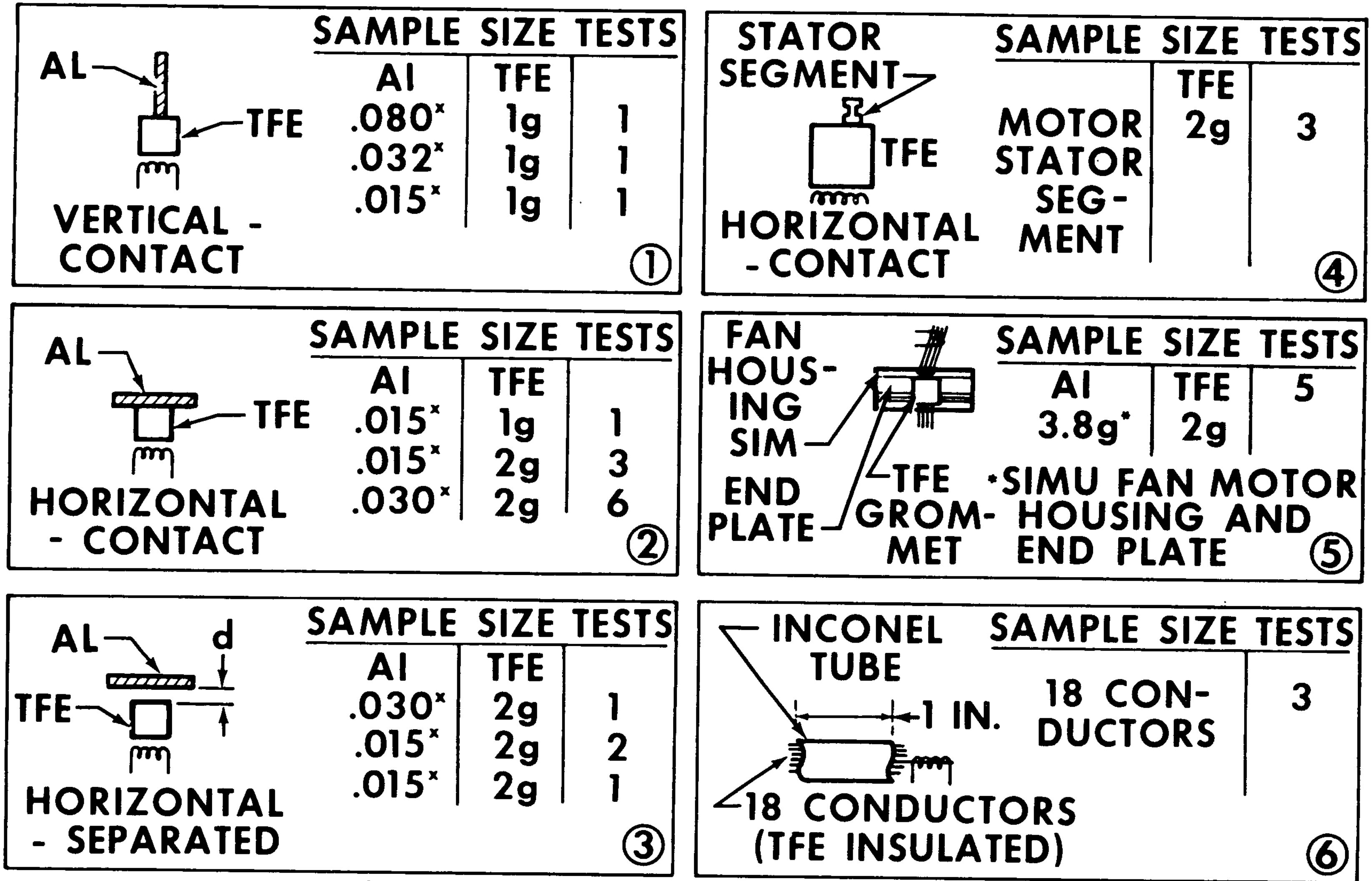
PROMOTED IGNITION TEST CONFIGURATIONS



[x]THICKNESS cm

Figure 4.

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PARTIAL CONFIGURATION TEST APPARATUS

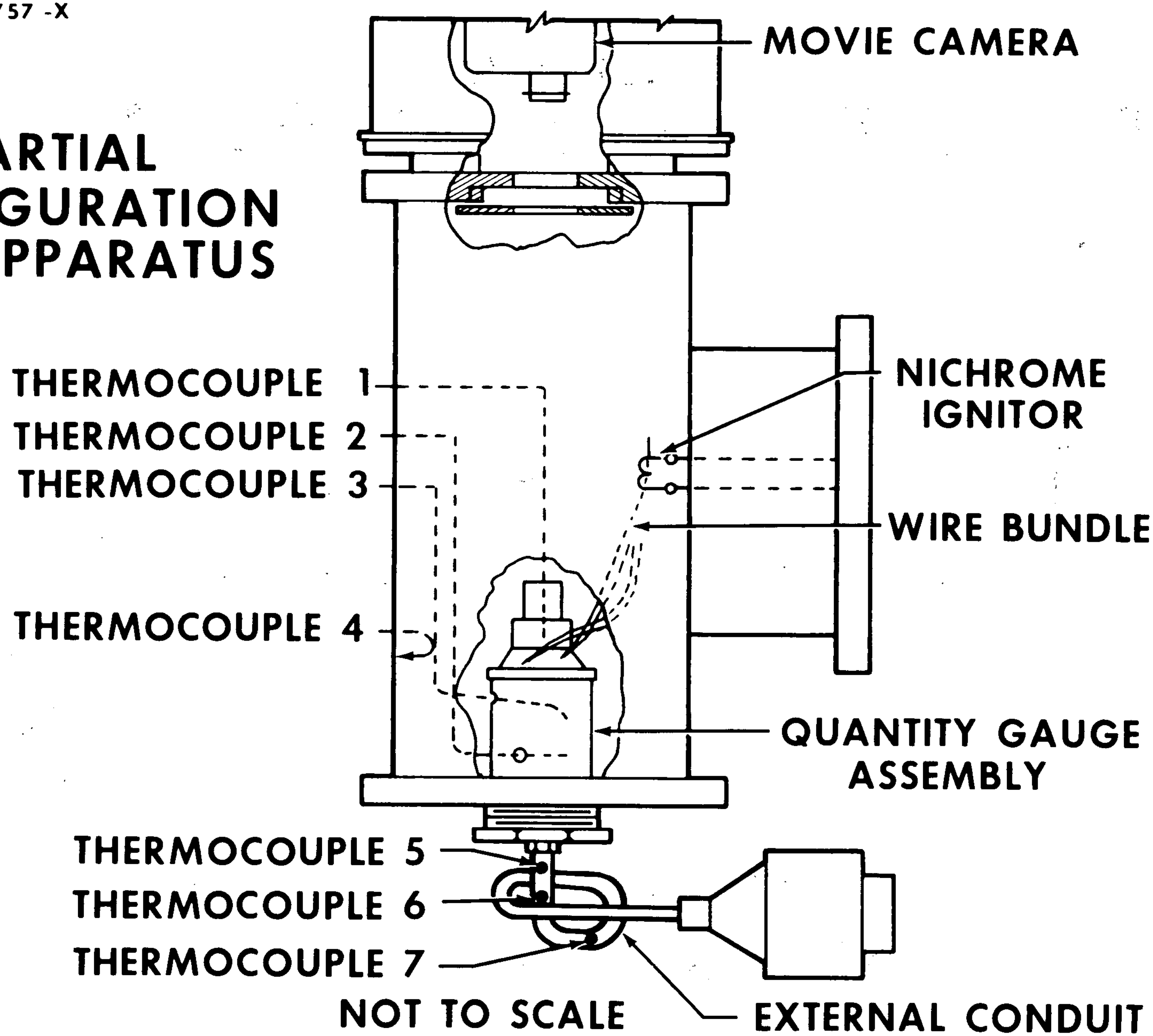

Figure 5.

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PRESSURE HISTORY OF PARTIAL CONFIGURATION TEST

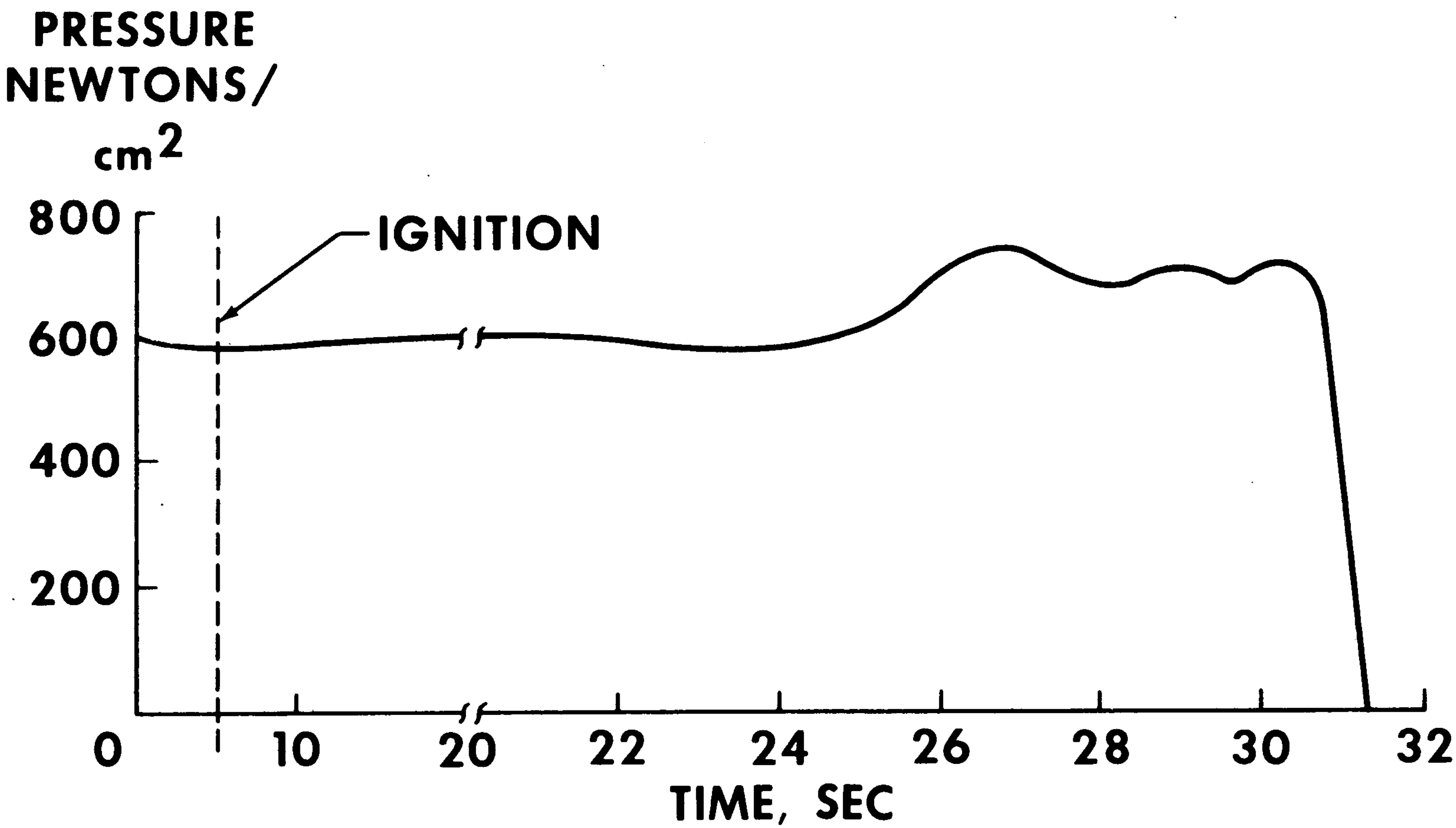

Figure 6.

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TEMPERATURE HISTORY OF QUANTITY GAUGE

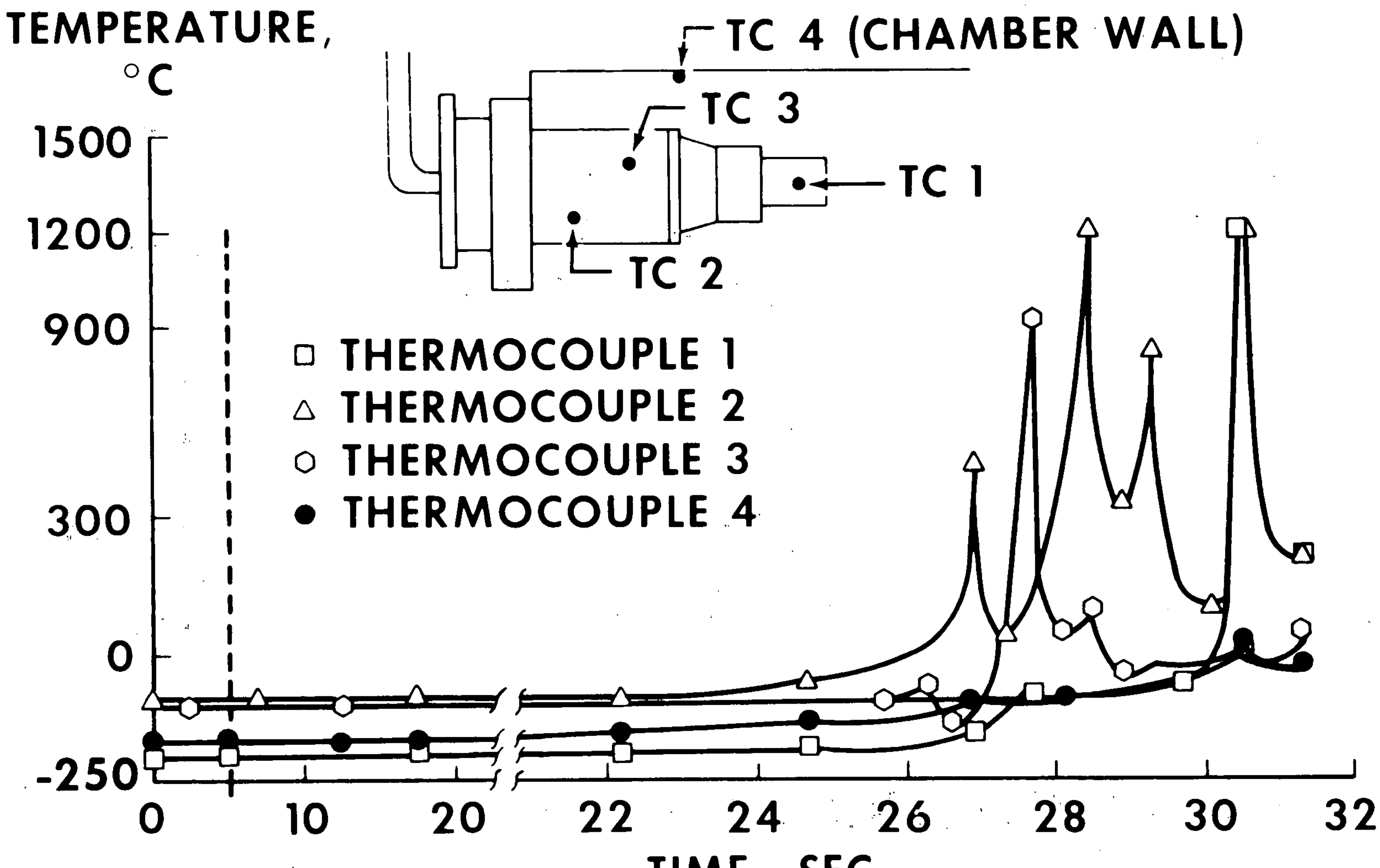

Figure 7.

NASA-S-71-1755-X

TEMPERATURE HISTORY OF EXTERNAL CONDUIT

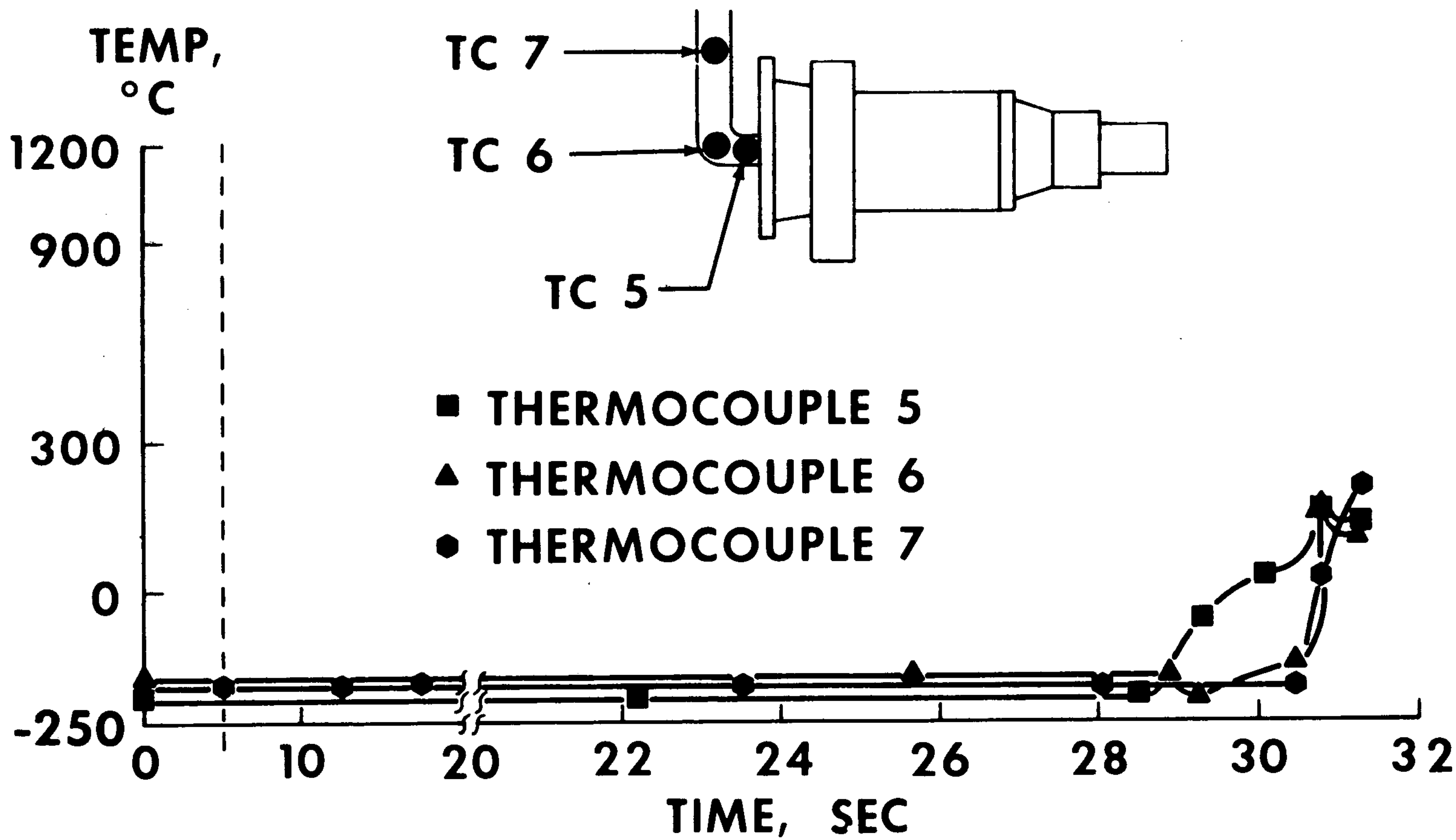

Figure 8.